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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of:)	DECLARATION OF HANS E. KIMMEL,
MADISON, Joel V.)	PH.D., UNDER 37 C.F.R. 1.132
)	
Serial No.: 10/776,555)	
)	
Filing Date: February 10, 2004)	
)	
Attorney Docket No.: EIC-401)	Examiner: KIM, John K.
)	
Title: THRUST BALANCING)	Group Art Unit: 2834
DEVICE FOR CRYOGENIC)	
FLUID MACHINERY)	
)	

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

DECLARATION OF HANS E. KIMMEL, PH.D., UNDER 37 C.F.R. 1.132

I, HANS E. KIMMEL, PH.D., HEREBY DECLARE AS FOLLOWS:

1. The following is true and accurate, and that this declaration is based on my own personal knowledge and on information and belief.
2. I make this Declaration in support of Applicant Joel V. Madison's Application No. 10/776,555 for Letters Patent entitled "THRUST BALANCING DEVICE FOR CRYOGENIC FLUID MACHINERY".
3. I am the Executive Director and Vice President of Research and Development for the Cryodynamics Division of Ebara International Corporation and have been employed with the company in this or similar position for 17 years. Ebara International Corporation is the

DECLARATION OF HANS E. KIMMEL, PH.D.
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Decl-HEK 032309-3.wpd

recognized world leader in the engineering and production of specialized cryogenic liquefied gas pumps and turbine expanders. See [www. Ebaraintl.com](http://www.Ebaraintl.com). I am an expert in the field of cryogenic material handling and cryogenic machinery design and manufacture.

4. I hold a Masters Degree in the field of Mechanical and Process Engineering from the T. U. University and a Ph.D. from the F. U. U. University in Munich, Germany, and have over 40 years of professional experience. I have conducted research at numerous nationally and internationally accredited institutions of higher learning and commercial entities. I have contributed to over 50 issued patents worldwide and have published numerous papers in advanced cryogenic technology. I have received recognition for my academic achievements both here in the United States as well as internationally.
5. I served as a member of the German Federal Board of Independent Professional Experts in the field of cryogenic rotating machinery from 1992 to 1998.
6. In September, 2004, I testified before the Federal Bureau of Investigation (FBI) in Washington, D.C., as an independent expert in cryogenic machinery in a special case of export violation of cryogenic pumps.
7. A true and accurate copy of Joel Madison's current Curriculum Vitae is attached hereto as Exhibit A. I have known and worked closely with Mr. Madison since about July, 1995. I am aware of and understand his invention entitled THRUST BALANCING DEVICE FOR CRYOGENIC FLUID MACHINERY and his related pending patent application U.S. Serial No. 10/776,555 filed Feb. 10, 2004 thereon.
8. Additionally, I have reviewed the Final Office Action mailed January 30, 2009. The Examiner is clearly very skilled and detailed in the review and examination of the Patent Application. It is evident that the Examiner has invested substantial time in the due diligence review of this Application, which shows throughout his review and is appreciated. In general, I agree with

many of his comments, but not necessarily the context from which they were taken, i.e., with respect to the prior art. In essence, I feel that the Patent Application is specific in the field of submerged cryogenic generators directly coupled to turbines and cryogenic pumps. The simple electric motor patents indicated as prior art due indeed have some similarity, but lack the basic physics and application for which the patent application is intended. For this reason, I request the specific comments below be considered before a final decision on the Patent Application be made.

9. Thermal shrinkage of processing and handling equipment and components used for cryogenic fluids is an inherent problem. Handling and processing equipment is subject to thermal shrinkage based upon thermal properties, including the coefficients for thermal expansion, of the materials used in said equipment and components. Thermal shrinkage effects have overall enormous impact upon design and operation of cryogenic fluids handling and processing equipment and components. It is known, for example, that the length of a full-size cryogenic fluid tanker ship will undergo a 2-meter or more shrinkage in overall length due to decrease in temperature associated with holding cryogenic fluids. Techniques and equipment designed to operate economically and safely under these extreme cold environments have taken decades to develop.
10. Publication entitled Application of Aerospace Research on Cryogenic Fuel Technology by Mr. Madison from the Aerospace Institute of Aeronautics and Astronautics conference held January 15-18, 1996 in Reno, Nevada USA is attached hereto as Exhibit B. Historically, cryogenic pumps were developed from the cryogenic rocket fuel pumps utilized in aerospace engineering. As shown in Exhibit B, the TEM design utilized in aerospace applications was without the spacer of the present invention. Those aerospace-related rocket fuel pumps didn't have and after 30 years still don't have the TEM with spacer. I do not believe that Mr. Madison's improvement with respect to submersible cryogenic generators and pumps was obvious in view of prior art related

to aerospace-related rocket fuel pump technology.

11. For almost 30 years, the size and speed of vertical cryogenic turbine generators and pumps was limited. As increased size had negative ramifications to the machine reliability, cryogenic turbine generators and pumps were limited by maximum “breakaway” speeds as well as there being limitations on bearing size, shaft diameter and overall machine diameter.
12. Thermal shrinkage due to extremely low temperature operation and processing of cryogenic fluids through vertical cryogenic turbine generators and pumps is completely unrelated to thermal expansion of hot components in conventional, electric motors. Electric motors convert electrical energy into mechanical energy by creating a magnetic field around wound coils of metal wires while conducting electrical energy. Heat is generated in electric motors by flow of electricity and mechanical rotation of the coils. The cited prior art by Fisher et al. and Agnes et al. teach the use of spacers to increase the length of the rotating mechanical rotors for brush-type contact or electronically commutated brushless motors to compensate for *thermal expansion* of other rotating and non-rotating components.
13. In the instant invention, the problems are associated with *thermal shrinkage*, not expansion. In the case of a cryogenic pump, mechanical energy is added to the cryogenic fluid. In the case of the cryogenic turbine generator, mechanical energy is created by expansion of cryogenic liquid. Neither of these operations are “analog” to creating mechanical energy by conversion of electrical energy. Moreover, the equipment and components of the present invention are not related to those found in electric motors. In electric motors, there s no analog for shaft-mounted cryogenic fluid product -lubricated type ball bearings. In electric motors, there is no analog for vertical flow of cryogenic fluid. In electric motors, the effects of thermal expansion are independent of orientation, i.e., the spacer compensates for thermal expansion of non-rotating components.

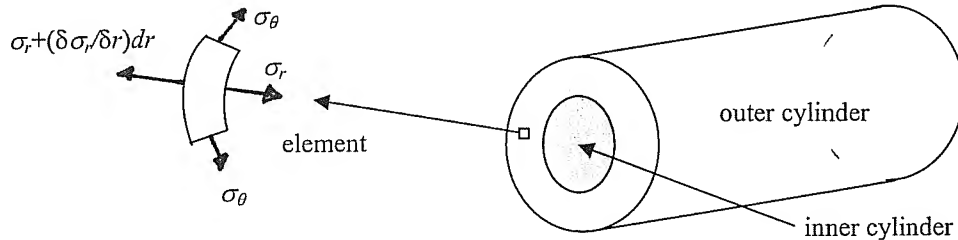
14. In the present invention, as described in the specification at page 4, line 7, through page 5, line 17, the specific problem is associated with the operation of thrust equalizing mechanisms in vertical cryogenic fluid turbine generators and pumps. During rotation, the shaft 4 and all its rotating components move upwards due to a differential in diameter between upper wearing ring 22 and lower wearing ring 24. Leakage flow at upper wearing ring 22 is reduced as variable orifice 20 closes, causing fluid pressure in chamber 18 to increase. The increased pressure in chamber 18 reverses the thrust which then acts in a downward direction. This causes the rotating assembly to move downward, thereby opening the variable orifice allowing the pressure in the chamber 18 to decrease. In the cited prior art related to electric motors, there is no analog structure or function for the thrust equalizing mechanism associated differential diameter set of wearing rings, variable orifice 20, increase in pressure in fluid chamber 18 or reversal of thrust forces acting on a rotating assembly.
15. Additionally, the stationary spacer 268 of Fisher et al. and the spacer 54 of Agnes et al., both of which extend the length of the rotor, cannot be considered analog to length compensator 26 of the present invention. Length spacer 26 of the present invention is not integral with rotating shaft 4. Length spacer 26 of the present invention is interposed between the bearing block and stationary thrust plate 8, thus spacing the lower bearing 6 relatively higher, closer to an upper bearing. In the cited prior art references directed to electric motors, there is no analog to reduce the span between main bearings to offset the reduction in the critical speed resulting from an increased generator size.
16. In my opinion, the shrinkage of the spacer is not covered in Fisher et al. or in Agnes et al. In Agnes et al., the spacer shrinkage refers to radial shrinkage of an insulation tube item 54. This is not the same situation as claimed in the present invention which is related to lengthwise shrinkage for a solid press fit of a spacer *in the cryogenic environment*. The claimed spacer also

serves no electrical insulation function.

17. A detailed analysis of the present invention is useful for mathematically modeling the solution.

To illustrate the shrinkage differences between the cited prior art and the present invention,

consider first the case in Agnes et al., as sketched below for two concentric cylinders:



To describe the stresses in the outer element of material it is clear that

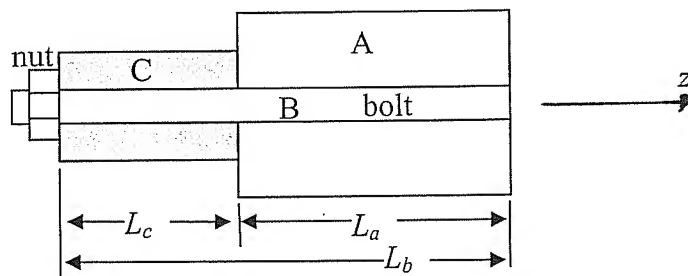
$$d\sigma_r / dr + (\sigma_r - \sigma_\theta) / r = 0$$

$d\sigma_z / dz = 0$ [Benham P., Crawford, R., & Armstrong C., (1996) Mechanics of Engineering

Materials (2nd edition), Longman Scientific Publishing, ISBN: 0582251648] The last expression

is important to indicate that no stress is produced in the z (cylinder axis axial) direction with the radial shrinkage of Agnes et al. insulation tube item **54**. This is due merely to the free boundary in the z direction seen in the Figure 7, item **54** of Agnes et al.

18. For the situation in the present invention, the spacer is bounded on its sides, and this in effect is a crucial requirement for the device to function. To illustrate, consider the sketch below which shows a spacer material C axially on top of a different material A with a 3rd material B as a bolt fastened through:



These are assembled at a warm condition, for example ambient temperature, with an axial prestress such that $d\sigma_z / dz \neq 0$. Selecting the material C so that its thermal expansion coefficient is very small (a material such as Invar) will, in effect, compensate for the thermal expansion of the other two materials A and B as the materials all get cold essentially simultaneously. This is particularly useful if A contracts axially in size more than B which could give relieve any prestress in the bolt B. Mathematically, let L_b , L_c , and L_a be the lengths of the shown bolt, compensator, and axial sleeve respectively. Also let x , y , and v be their respective thermal expansion coefficients. Thus, at a warm ambient condition:

$$L_b = L_c + L_a$$

Cooling all the materials to cryogenic temperatures gives:

$$L_b(x) = L_c(y) + L_a(v)$$

Thus, one can design or select the length of L_c to compensate, or preserve an axial prestress from the warm condition with the following logic:

$$L_b(x) = L_c(y) + L_a(v)$$

$$L_c(x) + L_a(x) = L_c(y) + L_a(v)$$

$$L_c(x) - L_c(y) = L_a(v) + L_a(x)$$

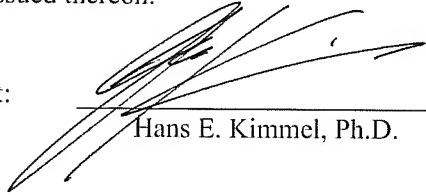
$L_c = L_a(v-x) / (x-y)$, so that in the cold condition, $d\sigma_z / dz \neq 0$. due to the compensated length, preserving the axial stress provided by L_c . Hence, the bearing described in the present

Application can be axially moved while still being secured in place axially, i.e., not loose. This situation is very different from the radial stress cited as prior art in the work of Agnes et al. It is hoped that with this additional clarification, the Examiner of the US Patent Office will reconsider the pending claims rejection.

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18. I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Title 18, United States Code, Section 1001, and that such willful statements may jeopardize the validity of the application or any patent issued thereon.

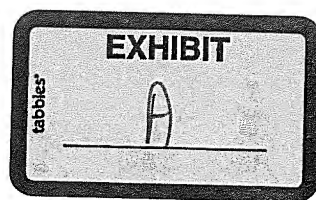
Declarant:



Hans E. Kimmel, Ph.D.

Date: March 23, 2009

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Joel V. Madison
Ebara International Corporation
Cryodynamics Division
350 Salomon Circle
Sparks, NV 89434

PROFESSIONAL EXPERIENCE

Feb 2003 to Present **Ebara International Corporation** *Sparks, Nevada*
Company designs, manufactures and tests submerged motor cryogenic pumps and power recovery turbines for the liquefied natural gas and petrochemical industries, distributes standard and engineered pumps for municipal and wastewater markets and manufactures a specialized line of electric motors/generators for cryogenic duties.

President/CEO

Responsible for all operations of the three divisions of Ebara International Corporation, Cryodynamics Division (Sparks, NV and London, UK), Electric Motor Division (Sparks, NV) and Standard Division (Rock Hill, SC). Close involvement in product development, marketing, sales, engineering, production and testing. Responsible for overall operating and capital budgets, financial performance, human resources, facilities maintenance, government regulatory compliance and contractual commitments for a company with annual sales of \$160 million.

Accomplishments:

- Managed 300% increase in sales over a three-year period. This included a 50% increase in staff and implementation of a multiple-shift system.
- Helped company turn a \$4 million loss into a \$12 million profit in less than 3 years.
- Managed sales strategy to maintain a 60% market share of the cryogenic submerged motor pump industry.
- Oversaw construction of new facilities and expansion of test stand to accommodate increased production demands.

Mar 2000 to Feb 2003 **Chief Engineer, Cryodynamics Division**

Responsible for the overall operation of the Engineering Department including areas of product design, test equipment design, procedure specifications, product testing, engineering standards, project management aspect of Engineering Department, department budget, overall guidance and decision-making regarding the Engineering Department. Responsibilities also included direction of the preparation of drawings, specifications, engineering calculations, bills of materials, manuals, test reports and test procedures.

Accomplishments:

- Designed, tested and marketed novel variable speed and fixed speed cryogenic power recovery turbines for natural gas liquefaction process. New design displaced competition's design at 2 operating plants, and achieved 90% order rate at new facilities.
- Designed, tested, and marketed new high-pressure cryogenic pump designs that allowed installation of ratings up to 3.0 MW. New design increased MTBO from ~8000 hours to 16,000+ hours and significantly decreased MTTO.
- Achieved customer confidence through technical presentations given with 90% order rate.
- Implemented 3-dimensional CAD system that enabled more efficient, robust designs while reducing lead-time for manufacturing.
- Substantially reduced warranty claims for products installed after 2000.
- Oversaw conversion of paper documentation to electronic data management system.

Mar 1997 to Mar 2000 **Project Manager, Cryodynamics Division**

Project Manager responsible for development, design, production and testing of hydraulic power recovery turbines for Oman LNG and MLNG Tiga projects. Supervised installation and commissioning of Oman LNG hydraulic power recovery turbines, LNG loading pumps and cryogenic process pumps.

Accomplishments:

- Satisfied Shell development release approval for Oman LNG hydraulic power recovery turbines, which included extensive analysis and testing for prototype and production machines. Design exceeded project efficiency requirements by >4%.

Mar 1995 to Mar 1997 **Project Engineer, Cryodynamics Division**

Project Engineer responsible for development, design, production and testing of cryogenic process pumps and LNG loading pumps for Nigeria LNG project and Ras Laffan LNG Project. Additional project engineering conducted for major LNG and LPG projects in India, Taiwan, China, Indonesia and Qatar.

- ***Accomplishments:***
Maintained on-time delivery and compliance to project specifications for all projects that were supervised.

Mar 1988 to Rockwell International Corporation, Rocketdyne Division
Mar 1995 Canoga Park, California

Aerospace Propulsion Division of the former Rockwell International Corporation, now a division of the United Technologies Corporation.

Member of the Technical Staff, Level III

Work performed in the area of design and testing of subscale hypersonic scramjet components used in the National Aerospace Plane (NASP) engine concept. These engine components were manufactured and installed in testing facilities at the Naval Surface Warfare Center (NSWC) in White Oak, MD, the Arnold Engineering Development Center (AEDC) in Tullahoma, TN, and the Hypulse shock tube facility at the NASA Ames Research Center. A key role was played in the conceptual phase of the design process, as well as providing on-site support and post-test data analysis capabilities. Additional responsibilities included numerical modeling and analysis of complex fluid flow problems through finite element analysis and computational fluid dynamics.

EDUCATION

1986-1988 Pennsylvania State University, University Park, PA
Master of Science Degree, Aerospace Engineering,

1983-1986 University of Nevada, Reno, NV
Bachelor of Science Degree, Mechanical Engineering

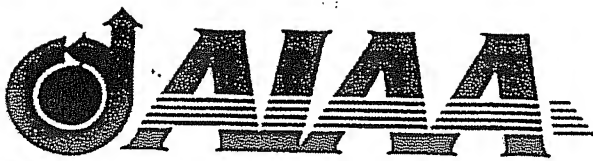
AFFILIATIONS

- American Society of Mechanical Engineers
- American Institute of Aeronautics and Astronautics
- Author or Co-Author of 8 technical papers

REFERENCES

Available upon request.





AIAA 96-0284

**Application of Aerospace Research On
Cryogenic Fuel Technology**

G. L. Weisser and J. V. Madison
Ebara International Corporation
Sparks, NV

**34th Aerospace Sciences
Meeting & Exhibit**
January 15-18, 1996 / Reno, NV

APPLICATION OF AEROSPACE RESEARCH ON CRYOGENIC FUEL TECHNOLOGY

G.L. Weisser, General Manager
and
J.V. Madison, Project Engineer
Ebara International Corporation
Cryodynamics Division
Sparks, Nevada

ABSTRACT

With an increasing demand for cleaner burning fuel sources for transportation and industrial applications there has been a rapid evolution of an entire industry devoted to the handling of liquefied cryogenic gases. Specialized equipment has been developed to meet the challenges associated with designing machinery capable of withstanding the rigors of operating at temperatures approaching absolute zero. A historical perspective of the development of this type of equipment is presented, with an emphasis on the technology that has been transferred directly from research conducted in support of the U.S. aerospace industry.

INTRODUCTION

Cryogenic fuels such as Liquefied Natural Gas (LNG) and Liquid Hydrogen (LH2) are emerging as viable alternative energy sources for vehicular transportation as well as industrial applications. The demand for cleaner burning fuels and the abundant natural reserves of LNG when compared to crude oil reserves are the major impetus behind the rapid growth of the industrial gases industry. The Federal Government and most states have now passed clean air legislation that encourages, and ultimately requires, transportation to further reduce emissions and guard against fuel leaks and spills. These regulations are making the costs of operating vehicles on conventional fuels rise. Natural gas is primarily composed of methane,

the simplest hydrocarbon structure, which makes it burn cleaner than any other fossil fuel, while providing the least carbon per unit of energy.

Liquid hydrogen fueled vehicles are being used in several pilot programs intended to explore the potential for reducing emissions in areas with severe pollution problems, such as Los Angeles and Mexico City. In addition to the reduced levels of emissions produced by LH2 powered engines, the overall thermal efficiency is approximately 32 percent higher than comparable gasoline powered engines.

The benefits derived from these fuels are driving the rapid growth of the industrial gases industry, which includes the production, processing, storage and ultimate delivery of these products into the global marketplace. Due to the large volume per unit mass of gaseous substances, the gases are liquefied to increase the energy density, facilitate transportation and allow for long term storage capabilities. As an example, transforming natural gas into LNG reduces its volume by approximately 600 percent. The process of liquefaction is achieved by refrigerating the gas below its boiling point, which ranges from -269°C for liquid helium to -1°C for liquid butane. The science of "Cryogenics Engineering," or producing cryogenic liquids and designing machinery capable of operating in cryogenic conditions has evolved almost entirely from the application of technology resulting from research conducted by the U.S. Aerospace industry.

PUMP DESIGN

Modern submersible pumps suitable for handling cryogenic fluids such as LNG, LH2 and other cold liquids present unique engineering problems that are not present in traditional centrifugal pump design. The pump shown in Figure 1 is a close coupled design with no rotating seals of any kind. This is made possible by allowing the electric motor to be entirely submerged in the pumping fluid with the pump proper. Advantages are derived from the fact that most cryogenic liquids do not conduct electricity, therefore the motor can be submerged without the danger of short circuiting the motor windings. The cold liquid also provides an excellent source of cooling for the motor and bearings. Some small losses are caused by the friction generated by the liquid within the motor space, which is filled with air for conventional motors. However, these losses are offset by the reduction in physical size and complexity of the mechanical systems afforded by this type of design.

The complete design process is described below, emphasizing the evolution of the equipment as a result of practical solutions to the problems encountered during the handling of liquified gases. These problems arise from the behavior of systems at extremely low temperatures, in addition to the dangers caused by the hazardous nature of many cryogenic liquids.

MATERIALS SELECTION

Detailed knowledge of the behavior of materials at extremely low temperatures is essential in designing any cryogenic system. Some widely used structural materials, such as high carbon steel, become extremely brittle at cryogenic temperatures and would lead to disastrous failures if used in this context. Other steel alloys, including austenitic stainless steels, exhibit increased strength at low temperatures with no accompanying loss of ductility.

Due to the increased demand for rocketry applications in the mid 1960's, the Air force Ballistic Missile division initiated a comprehensive effort to compile the mechanical and physical

properties of materials suitable for cryogenic service. The agencies contracted to perform this work were the National Bureau of Standards Cryogenics Engineering Laboratories in Boulder, Colorado, and the Martin Company, Denver Division. A wide range of materials, including aluminum alloys, stainless steel alloys, titanium, superalloys, polymeric materials and fiber-reinforced plastics were tested, with the results being maintained by the Air Force Materials Laboratory.

During this research it was found that the ductility of metals having the face-centered cubic crystal structure is relatively insensitive to a decrease in temperature, while metals of the crystal lattice type show a tendency towards brittleness at low temperatures. This relationship can be understood on the basis that the face centered cubic lattice has more slip systems than the crystal structures, which makes the crystal lattice less effective in assisting dislocation motion at low temperatures¹. Thus, among metals and alloys normally considered for structural purposes, copper-nickel alloys, aluminum and its alloys and the austenitic stainless steels that contain more than approximately 7 percent nickel, all face-centered cubic, remain ductile down to the lowest temperatures to which they have been measured. Iron, carbon and low-alloy steels, molybdenum, and other body-centered cubic materials become extremely brittle at low temperatures. The ductility and impact strength of various materials as a function of temperature are shown in Figures 2 and 3. Note that for some materials an abrupt transition in impact strength and ductility occurs at low temperatures, caused by a solid-solid transition, making them unsuitable for use in cryogenic systems.

For any machine to operate within specified tolerances at cryogenic temperatures, the exact amount of thermal contraction a material will experience while being cooled from ambient conditions must be known. As demonstrated in Figure 4, the linear coefficient of thermal expansion varies with temperature, with the face-centered materials showing a somewhat larger variation. In some cases the various expansion rates of these materials can be used wisely to

facilitate machine design and reduce the mechanical complexity of the equipment. For instance, in a multi-stage pump design a martensite stainless steel ring is used as a seal between the aluminum alloy housings. Referring to Figure 1, the components form a tight sealing surface at operating conditions, but due to the difference in thermal expansion there is a large clearance at ambient temperatures, allowing for ease of assembly and eliminating the need for special tools.

The thermal conductivity exhibited by materials also influences the selection process, as thermal shock must be avoided while cooling the system down to low temperatures. Aluminum alloys have excellent thermal conduction characteristics in addition to adequate ductility and thus are generally used for larger pump components. The relatively low strength of these alloys is not a concern because the pumping unit is normally installed inside of a vessel or column constructed of stainless steel, which has sufficient strength to absorb large forces and moments resulting from piping loads (see Figure 1).

FLUID PHYSICAL PROPERTIES

The physical and thermodynamic properties of cryogenic substances are also essential to any design, but are not readily measurable. Recognizing that knowledge in this area was essential to the aerospace industry, NASA sponsored a research project in 1964 to determine the physical properties of the most common liquified gases and compile them in a single source. The contractor selected for this work was the Missile and Space Systems Division of Douglas Aircraft company located in Santa Monica, California. Thorough testing was performed on the most widely used cryogenic substances at the time, helium, hydrogen, oxygen and nitrogen. The results were published in the "Cryogenic Fluid Properties Handbook."²

A similar study was conducted by the National Bureau of Standards in Boulder, Colorado, for substances such as LNG and liquid fluorine. The results were compiled in "A Compendium of the Properties of Materials at Low Temperatures,

Phases I and II."³

INTEGRAL SUBMERGED MOTORS

When the first cryogenic machinery was developed and tested it became apparent that seals and bearings for rotating devices would present major difficulties in operation due to the extreme temperature gradients encountered in the system. It was found that the shaft would conduct the cold to the interior of the electric motor, causing condensation in the motor coils; the seals would leak hazardous product, causing the potential for an explosion; and the formation of ice on the coupling caused severe vibration problems. One method of circumventing these problems was to develop an integral pump and motor unit that was completely immersed in the pumping liquid. This type of equipment was already being used in the mid 1960's for in-flight refueling of fighter aircraft, using JP-4 or kerosene as the transfer fluid.⁴

For an electric motor to function while immersed in fluid requires that the fluid will not conduct electricity or chemically attack the materials of the motor, which would cause an electrical breakdown and failure of the equipment. Fortunately, the electrical strength of LNG has been shown to be very high, and for all practical purposes can be considered as a dielectric substance.⁵ Figure 5 shows the breakdown voltage of LNG as a function of electrode spacing, which shows that the value is 400 volts with zero gap.

These properties allow the entire integral pump and motor unit to be located within the pumping liquid. A typical LNG cargo ship installation is shown in Figure 6. It is interesting to note that there is no risk of fire or explosion with this type of system since the storage containers are devoid of air/oxygen. Several design problems are eliminated with a submerged motor since no dynamic seals are necessary, no long shafts subject to differential thermal expansion are present and the motor is effectively cooled by circulating a small amount of the pumping fluid directly through the motor itself.

New manufacturing techniques were

required for the large scale electric motors used for cryogenic service to assure reliable operation. One source of problems encountered by early versions of submersible cryogenic motors was the residual humidity and air bubbles imbedded in the insulation system, causing electrical breakdowns when subjected to low temperatures. The problem of resistance to humidity has been resolved by using vacuum pressure impregnation insulation systems. This procedure entails the use of epoxy resins which are applied under a double cycle of immersing the motor stator in special epoxy materials within vessels that can be subjected sequentially to a vacuum then a high pressure. This assures that all air bubbles are removed from the epoxy and stator by the vacuum and that the epoxy is forced deep within the stator cavities by the pressure. Following immersion, the impregnated stators are then subjected to a second cycle of immersion, vacuum, pressure and curing. This double VPI procedure has proven to yield stators that are capable of achieving 20 years of continuous LNG service.⁴

The submersible cryogenic motor solves many of the engineering problems associated with cryogenic pumps, however special consideration is necessary to ensure the electric motor will start at low temperatures. Since the electrical characteristics of the motor change at low temperature due to resistance and magnetic changes, the available starting torque of a motor is significantly decreased at lower temperatures. As seen in Figure 7, the peak of the torque versus speed curve is close to the pull-in speed of the motor for cryogenic conditions, and this effect is exaggerated by reduced voltages normally encountered during the starting sequence. Therefore, proper testing should be conducted to verify and demonstrate that the motor has sufficient starting torque at field operating temperatures with the motor receiving minimum expected starting voltages and with the maximum expected loads on the shaft. Due to the hazardous environments in which the equipment is normally located, it is critical that the motor performance at operating temperature is proven before installation of the pump. To verify this, the entire pump and motor assembly should be mounted in a liquefied

gas test facility similar to that shown in Figure 8.⁶ Then, using LNG as the test fluid to be pumped, the motor starting capability can be demonstrated at the proper temperature, voltage and dynamic loading conditions.

BEARING DESIGN

The type of motor previously described also requires the bearings to be immersed in the pumping fluid. Other cryogenic systems being developed in support of the space program prompted NASA to conduct an experimental program to determine the behavior of bearings at cryogenic temperatures using the product as a lubricant. It was found that ball bearings constructed of martensite stainless steel with polytetrafluoroethylene (Teflon) separators would perform adequately at low temperatures since the environment offers optimum cooling even though the viscosity of the fluids are very low. For example, the viscosity of LNG is approximately 0.109 cP, or about one-hundredth of the value of normal lubricating oils. The viscosities of the most common cryogenic hydrocarbons as a function of temperature are shown in Figure 9.

Although the bearing will function at these temperatures, due to the low viscosity the axial loads must be eliminated to ensure adequate service life.⁷ For this purpose, a two-orifice system can be built into the pump components, as shown in Figures 10 and 11. The upper wearing ring shown in Figure 10 is larger in diameter than the lower wearing ring, causing in a net resultant force in the upward direction. Due to this upward force, the pump shaft and all of its rotating components are forced upward, the impeller throttling ring reducing the clearance between it and the stationary plate, thus restricting the wearing ring leakage flow and causing the pressure in the upper chamber to increase as shown in Figure 11. Due to the increased pressure in the upper chamber, the thrust is reversed and now acts in a downward direction. This causes the rotating assembly to move downward, thereby opening the passage between the stationary plate and the impeller throttling ring, allowing the pressure in the upper chamber

to decrease. The opening between the stationary plate and the impeller throttling ring then adjusts automatically to produce pressure in the upper chamber sufficient to offset the upward thrust.

Continuous self-adjustment by this type of thrust equalizing mechanism allows the product lubricated ball bearing to operate at zero thrust load over the entire equipment capacity range, thereby greatly extending the service life of the bearings and reducing maintenance requirements. This design has demonstrated the potential for thousands of hours of maintenance free operation in the field. The length of time between overhauls is very important, as special precautions must be taken when servicing the equipment due to the inflammability of the product liquid. In most cases the vessel must be purged of all product and filled with an inert substance such as nitrogen gas when installing or removing the equipment.

CONCLUSIONS

Submersible motors of the type described have become the standard for present methods of cryogenic liquids storage and transportation, which is dominated by the LNG industry. A typical LNG storage facility has one or more large industrial centrifugal pumps located inside of each storage tank to transfer the fluid to a cargo ship or directly to a pipeline supply system. Similarly, the LNG cargo ships have a series of pumps located inside of the on-board storage containers. These pumps are capable of transferring up to 120,000 cubic meters of LNG in a few hours, with motor sizes in the range of 575 kW. In the near future, these requirements are expected to increase to over 200,000 cubic meters capacity, with motor ratings over 1000 kW. The transfer of large amounts of cryogenic fluids would be impossible without the benefits derived from the submersible pump and motor unit technology developed through the research provided by the aerospace industry over the years. With the expanding market demand for LNG powered transportation there will be an increased requirement for storage and transfer facilities of all sizes, ranging from the cargo transportation

described earlier to local vehicle filling stations.

In addition to LNG, liquid hydrogen is expected to become a common transportation fuel in the immediate future, with applications in air travel, rail transportation, mass transit and personal vehicles. Major automobile manufacturers such as BMW currently have prototype vehicles equipped with hydrogen powered engines, which could be introduced into the market whenever mass hydrogen production becomes available. A recent study conducted by the Aerospace Corporation³ regarding alternative vehicle fuels concluded that LH2 powered automobiles have been proven to be the lightest in weight, have the lowest total cost of ownership, be the most suitable for design ranges above 85 miles and have the lowest source energy consumption for the 1990 model year. The transition from gasoline powered automobiles to hydrogen power will likely be implemented by the widespread introduction of LNG fueled vehicles as a first step, due to the similarities between LNG and LH2 and the ease of engine conversion. Similar projects are progressing in the commercial aerospace industry, with a cooperative program between Germany and Russia expected to yield a production version of an LH2 powered "Cryoplane" within 15 years.

In order to keep pace with the projected growth of this industry, further improvements in the design of cryogenic fluid handling and storage equipment will be necessary. In fact, the most economical means of mass LH2 transport will be by air, requiring the development of a fleet of LH2 air tankers to meet the expected market demands⁹. Current aerospace projects are expected to lead to improvements in cryogenic processing equipment in the near future as well. One example is derived from the Space Transportation Main Engine (STME) which is fueled by LH2. In order to improve the high pressure turbopump performance for the STME, hydrostatic journal bearings were developed using LH2 as the pressurized lubricant source. These bearings provide the shaft with reduced running friction, higher stiffness and reduced weight when compared to the ball bearings used in the Space Shuttle Main Engine (SSME) turbopumps,

resulting in significantly increased engine performance. These bearings have the potential for a nearly unlimited service life, whereas ball bearings are responsible for many of the engine failures that occur in cryogenic applications. The use of hydrostatic bearings for future generations of cryogenic pumps is expected to result in increased performance and reliability. It has been demonstrated that the vast majority of the cryogenics industry has evolved from advancements in technology driven by aerospace research in the past, and this trend is expected to continue well into the future.

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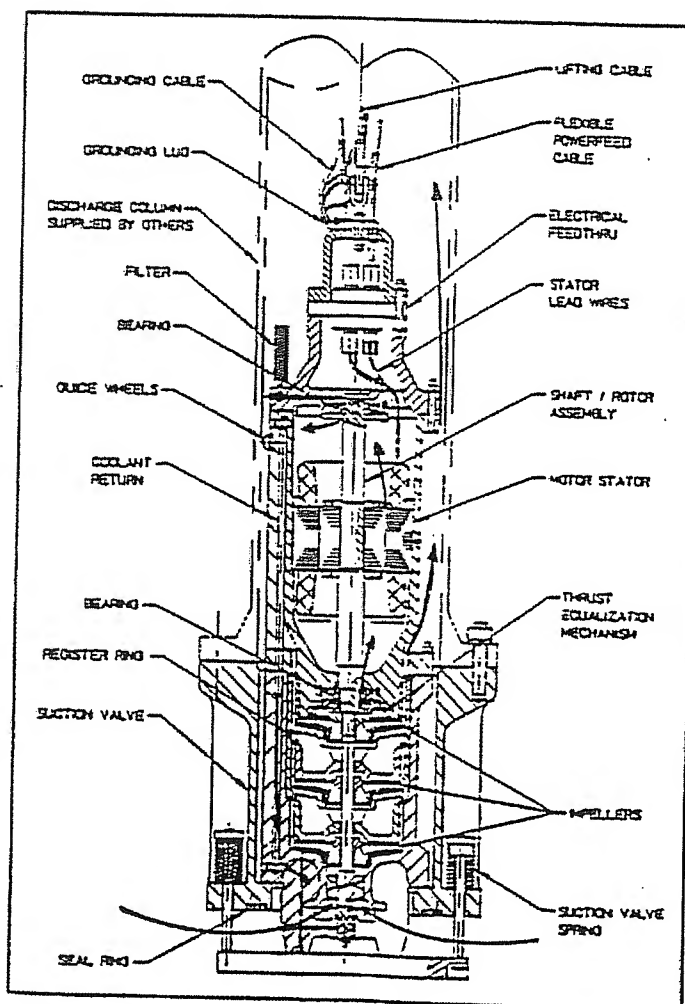


Figure 1. Multi-stage submersible cryogenic pump. The bold arrows indicate primary discharge flow and cooling circulation.

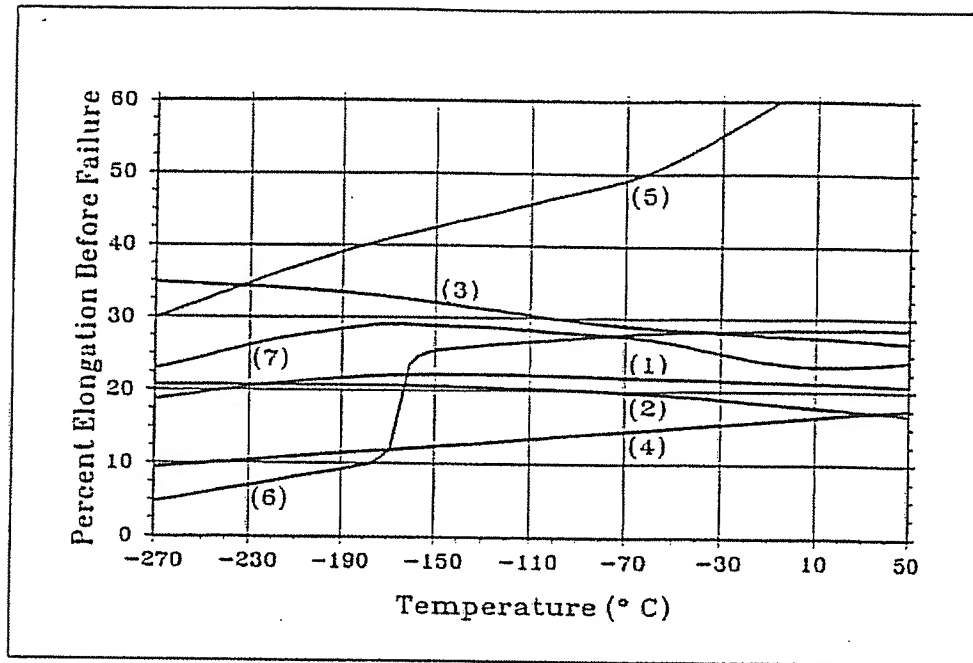


Figure 2. Percent elongation for various materials versus temperature. (1) 2024 T4 aluminum; (2) beryllium copper; (3) K Monel; (4) titanium; (5) 304 stainless steel; (6) C1020 carbon steel, (7) 9 percent Ni steel.

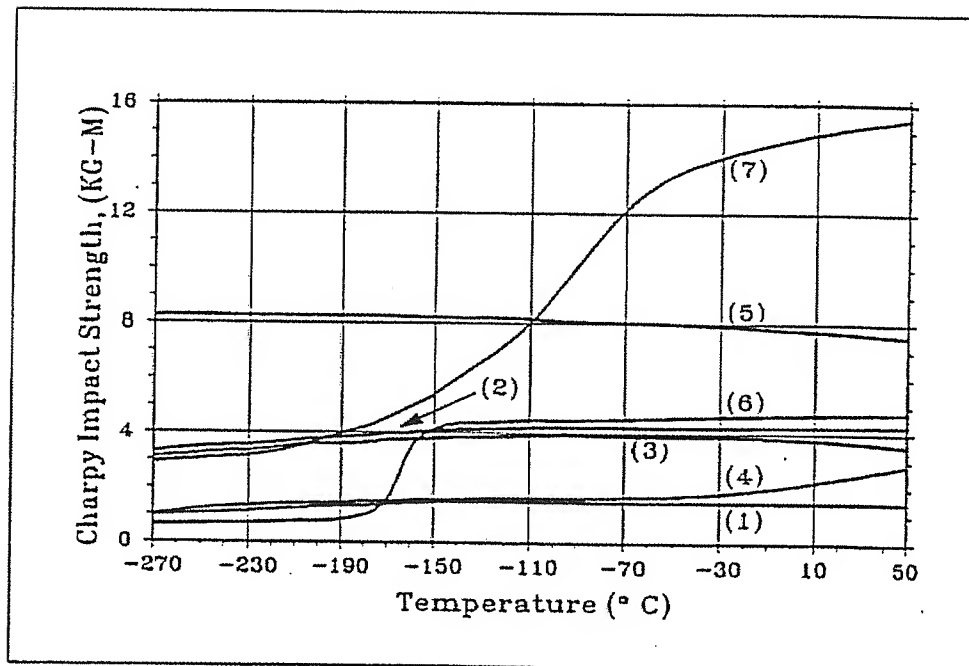


Figure 3. Charpy impact strength at low temperatures. (1) 2024 T4 aluminum; (2) beryllium copper; (3) K Monel; (4) titanium; (5) 304 stainless steel; (6) C1020 carbon steel, (7) 9 percent Ni steel.

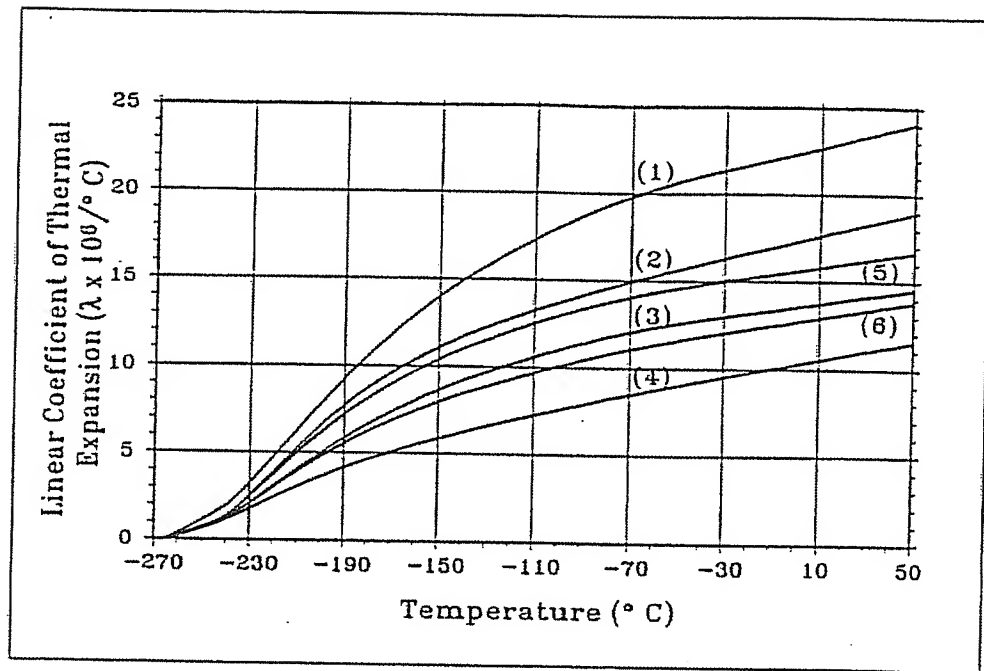


Figure 4. Linear coefficients of thermal expansion. (1) 2024 T4 aluminum; (2) beryllium copper; (3) K Monel; (4) titanium; (5) 304 stainless steel; (6) C1020 carbon steel.

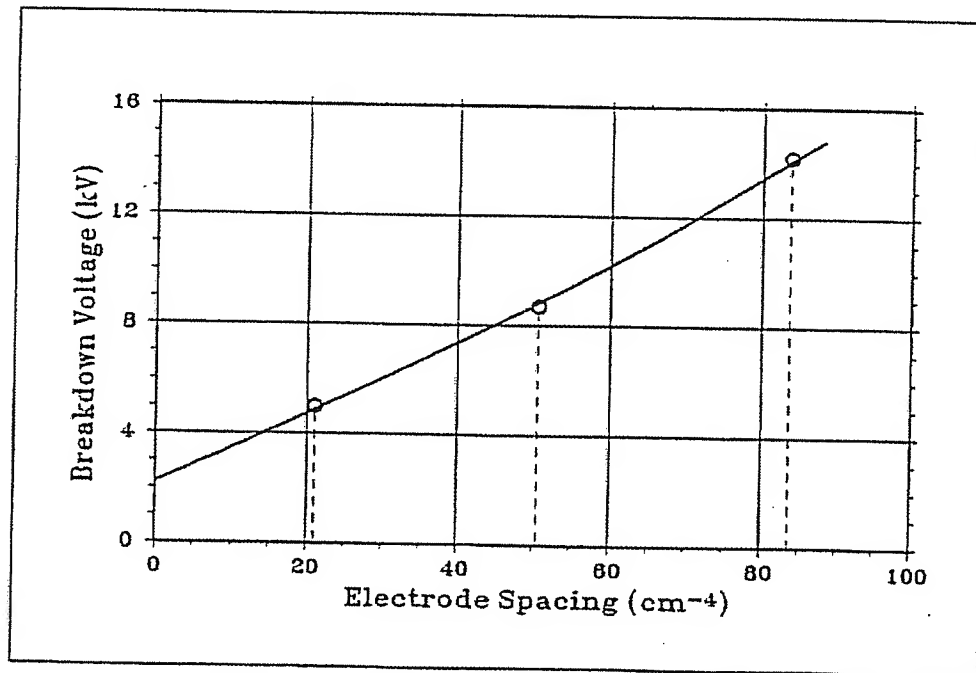


Figure 5. Breakdown voltage versus electrode spacing for methane. Stainless steel electrodes, zero O.P.

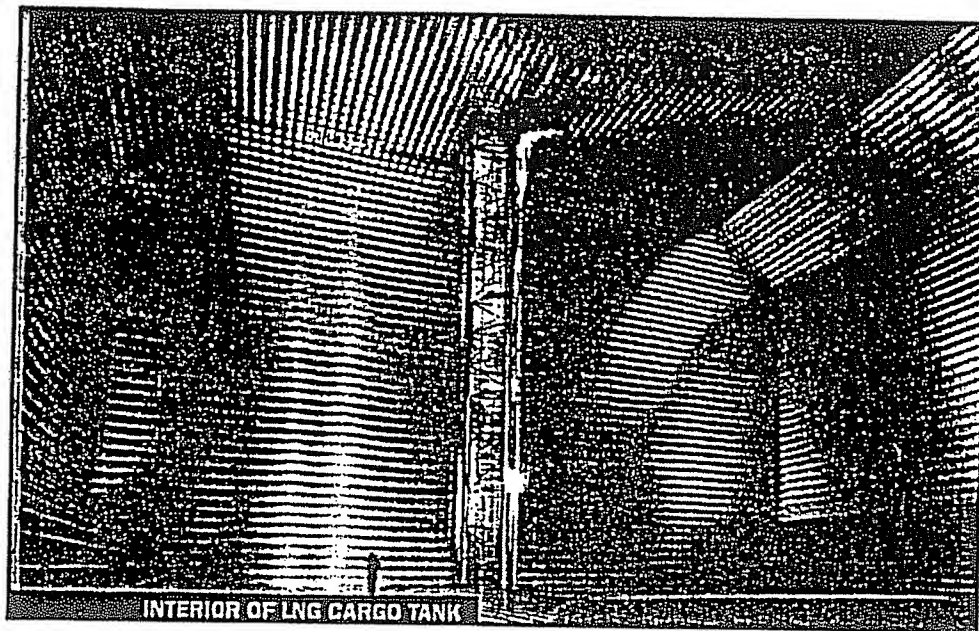


Figure 6. Interior of storage container of LNG cargo ship. Submersible pump is shown installed in bottom center.

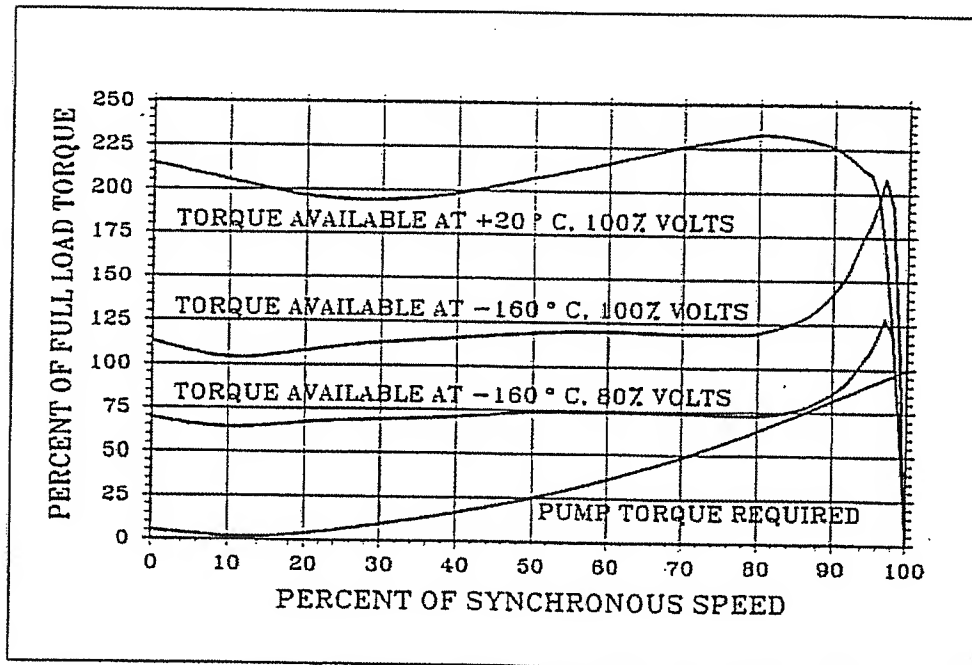


Figure 7. Electric motor torque characteristics at ambient and low temperature.

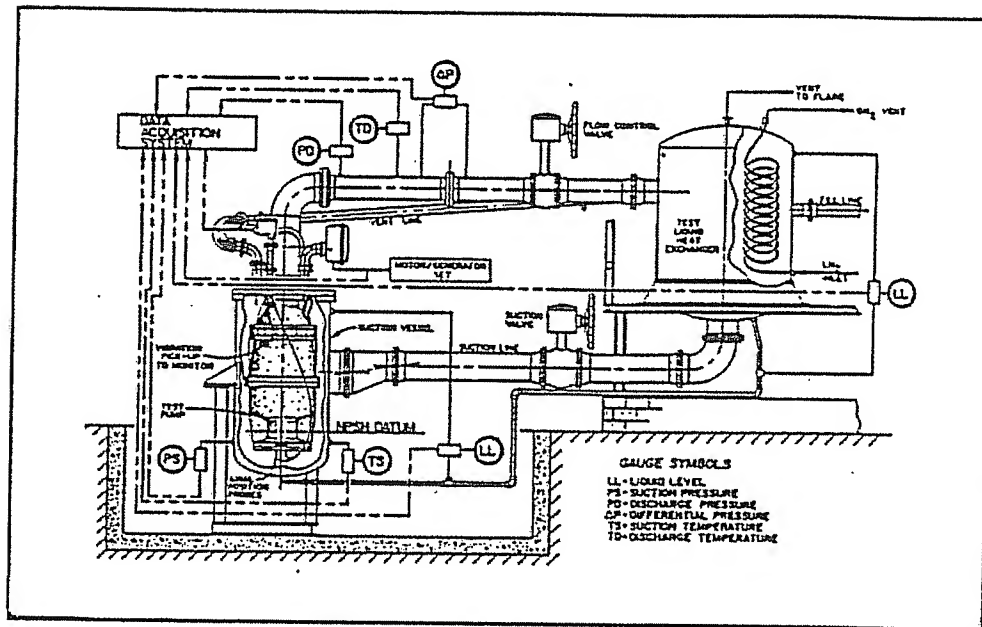


Figure 8. Cryogenic test stand flow schematic.

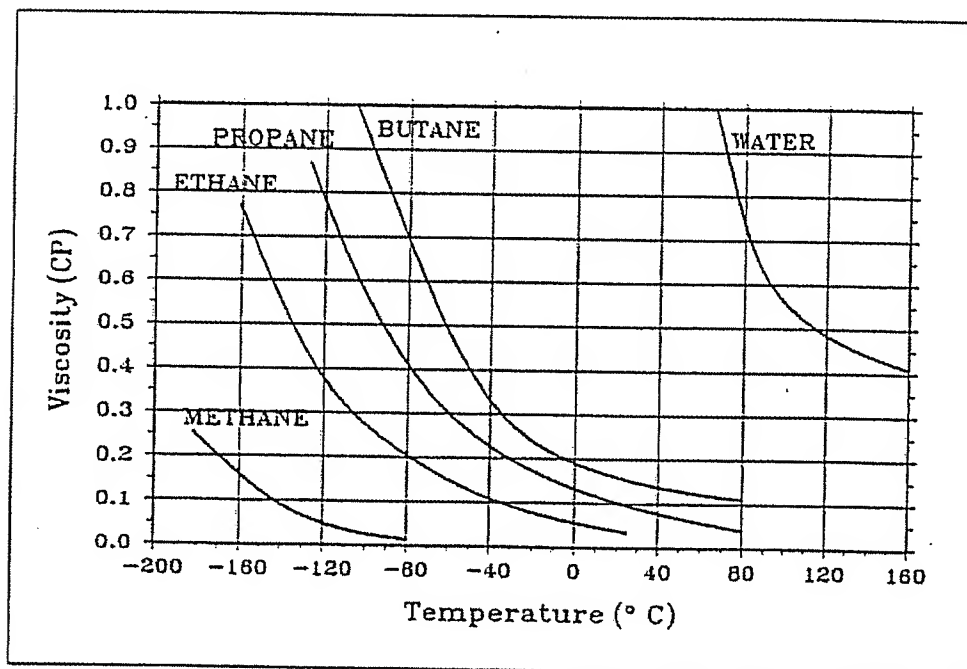


Figure 9. Viscosities for various liquefied gases. Water is shown for reference.

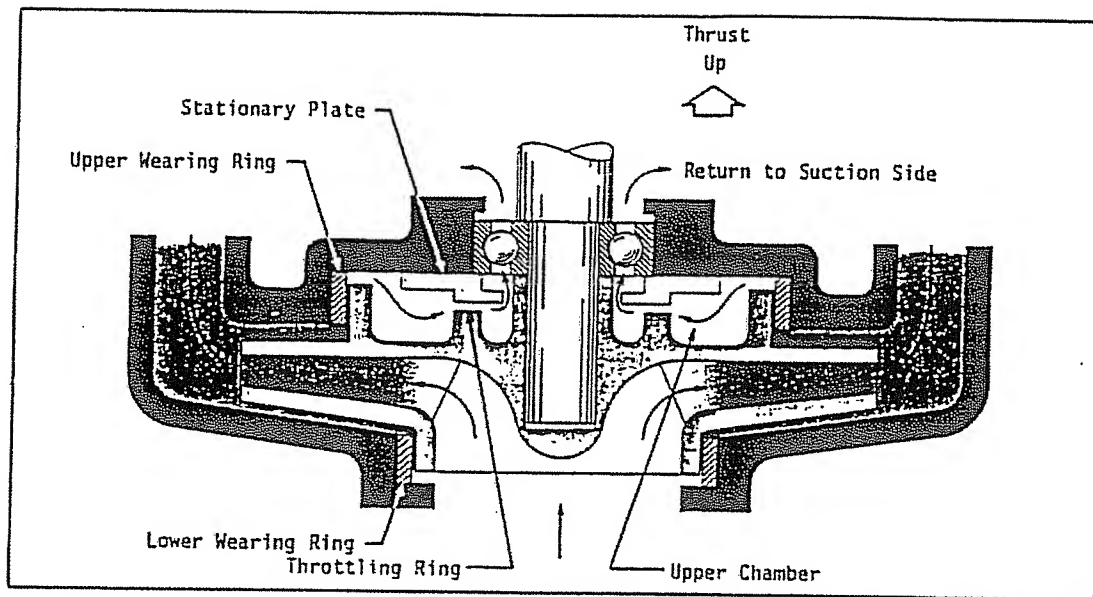


Figure 10. Schematic of thrust equalizing mechanism.
Shown in up-thrust condition.

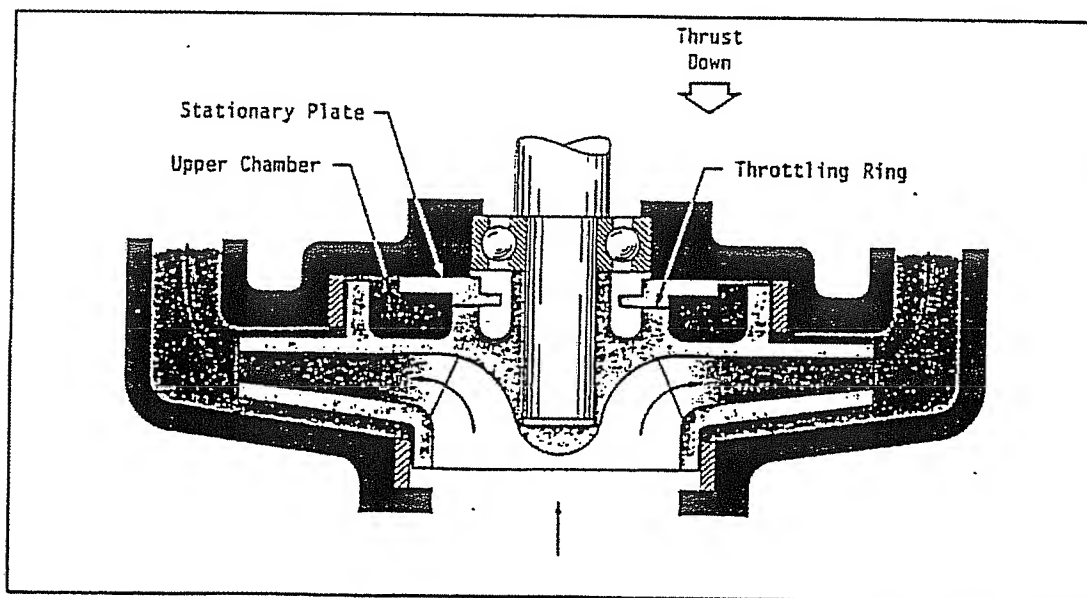


Figure 11. Schematic of thrust equalizing mechanism.
Shown in down-thrust condition.